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Title:	Europe's energy policy based on large-scale use of renewables most likely will require supplemental power supplies to balance their electrical power systems
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Europe's energy policy based on large-scale use of renewables most likely will require supplemental power supplies to balance their electrical power systems.

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Political decisions toward an increased role for renewable energy sources (wind & solar) in Europe will have an impact on the functioning of the electrical power systems that will have to be offset due to the inherent intermittent nature of renewable sources. The offset can be accomplished either through increasing non-renewable energy supply and production from other means, including purchasing Russian piped natural gas and LNG, or decreasing demand by curtailing power consumption. Europe likely will also need increased energy supplies to cover reduced gas production in the North Sea and Netherlands. Also, expected disconnection of Baltic states from the BRELL (Belarus-Russia-Estonia-Latvia-Lithuania) grid will force these countries to acquire electricity from Europe, resulting in increased demands on the European power grid that will require additional capacity to offset.

- The inherently variable nature of solar- and wind-based power sources require back-up power systems—power sources capable of quickly increasing their output, such as hydroelectric, gas and coal-burning plants or power storage solutions such as large-scale batteries.
- Gas remains a viable option to supplement and back-up the power grid, especially considering EU intentions to phase out nuclear and coal power plants and currently prohibitively expensive batteries. Gas-fired plants have demonstrated the most flexibility for accommodating a larger share of renewables on the grid.
- Currently, piped natural gas is cheaper than LNG and its delivery is more predictable (LNG-carrying ships can change their destinations en route to more profitable markets). It has proven easier to increase piped volume than ship-based deliveries.
- The EU may experience a gas deficit because of impending gas production closures in the Netherlands and declining gas production in the North Sea. This shortage must be made up for with other supply streams. Russian gas could potentially serve as a compensatory measure.
- The EU has built a distribution pipework for Nord Stream 1 and 2 gas. European energy corporations privately funded its construction and may pressure EU countries into energy policies that would allow the corporations to recoup these sunk costs.
- The end of electricity from BRELL for Estonia, Latvia, and Lithuania most likely will result in more pressure on European power sources.

Domestic political considerations are a primary driver of EU policy on energy. For example, one of the leading candidates to replace retiring German Chancellor Angela Merkel in autumn of 2021 has taken strongly anti-gas, -nuclear and -coal power stances and could prohibit using natural gas to balance energy production. It is not clear what the compensating option would be available other than potential cuts in energy use.

There are recent examples of increased natural gas consumption due to energy deficits that suggest it is a preferred option to bridge energy supply fluctuations.

Europe is committed to Green Energy

At the 7th International Conference Berlin Energy Transition Dialogue 2021 the EU confirmed its commitment to becoming “climate neutral” by 2050 and is legally bound to do so.¹

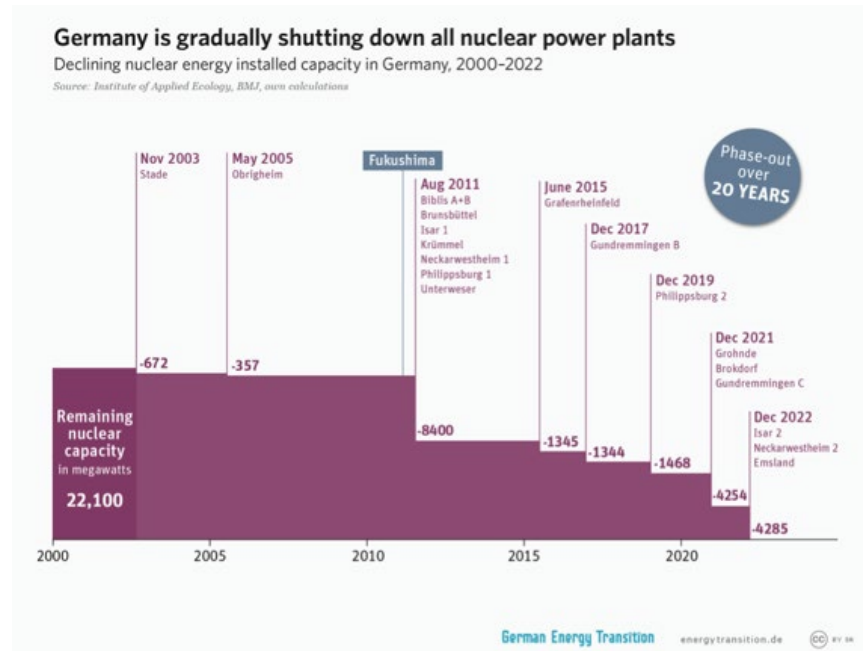


Figure 1. Gradual shutdown of German nuclear power plants in the near future²

European countries power policy decisions are decreasing the overall power generating capacity from nuclear, coal and hydroelectric sources. Europe decided to phase out nuclear and coal-burning power plants and environmental considerations make it difficult, if not impossible, to increase hydroelectric production capacity in the short to medium term. Tightening EU emission requirements will likely speed the retirement of coal power in Europe to as early as 2030.³ Strict hydropower⁴ regulations have

¹ EU reaches major climate deal ahead of Biden climate summit. AP News, 21 April 2021

<https://apnews.com/article/eu-major-climate-deal-ahead-biden-summit-4685d734b48fc73cce63806351103e2e>

² Renewable Energy in Germany Sets Records in March. CleanTechnica Journal. 17 April 2017.

<https://cleantechnica.com/2017/04/17/renewable-energy-germany-sets-records-march/>

³ The new EU climate target could phase out coal power in Europe as early as 2030. 27 April 2021. Science Daily.

<https://www.sciencedaily.com/releases/2021/04/210427094822.htm>

⁴ Guidance on the requirements for hydropower in relation to EU Nature legislation. European Union, 2018.

https://ec.europa.eu/environment/nature/natura2000/management/docs/hydro_final_june_2018_en.pdf

Europe Needs Russian Gas

resulted in declines in power production in Sweden, Austria, Spain and Italy.⁵ European countries have also experienced a consolidated effort from political groups to curtail hydropower generation.⁶

Inherently variable nature of solar- and wind-based power sources requires back-up power systems, which can consist of hydroelectric, gas and coal-burning plants, or batteries.

Production of power by windmills varies on daily, monthly and yearly cycles, creating a so-called “seesaw” (or zigzag) of windmill operations, underscoring its inherent variable nature. Solar production is also variable—intermittent during the day, shifting to zero at night and changing with the seasons (shorter days in winter, longer in summer in Europe). Below is a graph depicting production of electricity in the US based on energy source; solar generation has a strong cyclical nature that in the US is being compensated by natural gas:

U.S. electricity generation by energy source 4/18/2021 – 4/25/2021, Eastern Time

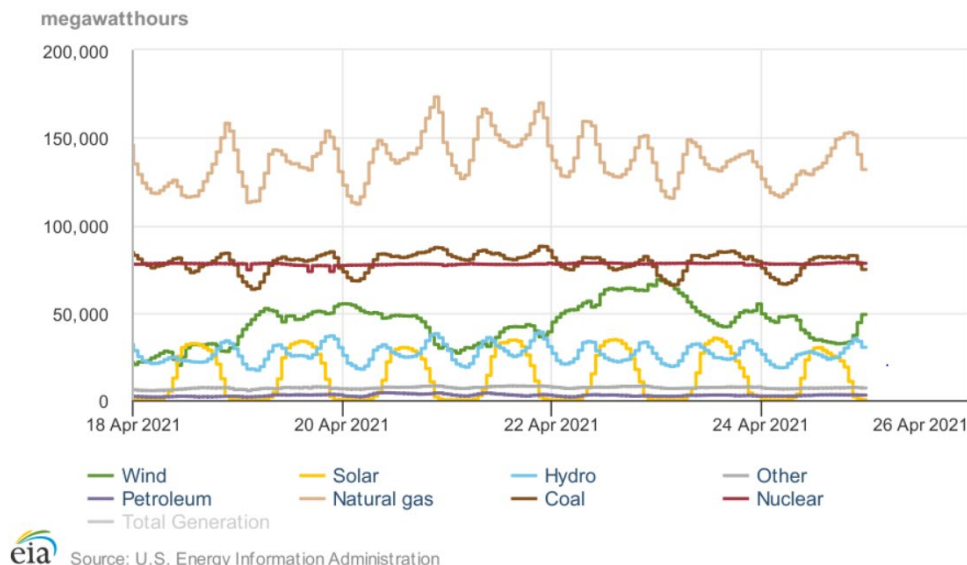


Figure 2. US data on electricity sources.

Wind and solar-based power generation can and does vary and must be supplemented during low/no production times. See Appendices A and B for more details.

⁵ European insights: hydropower, climate change in EU law. 12 November 2019. Water Power and Dam Construction Magazine. <https://www.waterpowermagazine.com/features/featureeuropean-insights-hydropower-climate-change-and-eu-law-7502217/>

⁶ “No More New Hydropower in Europe” a Manifesto. World Fish Migration Foundation. October 2020. <https://worldfishmigrationfoundation.com/wp-content/uploads/2020/10/STOP-NEW-HYDROPOWER-IN-EUROPE.pdf>

With EU intentions to rely more on wind and solar, gas remains an attractive option to back-up renewable power sources, as power storage solutions are currently prohibitively expensive.

The EU intends to increase usage of wind and solar introducing growing variability into grid operations, which have traditionally been based on coal, hydro, or nuclear power. The higher the share of solar and wind, the more the grid can experience fluctuations in energy production. These fluctuations must be aligned against changes in customer demand—higher during the working hours with peaks in the morning and evening and lower at night—and planned for to prevent supply constraints.

For a grid to operate reliably it must have options in place to quickly compensate for output variation by renewables—up to 100% supply replacement. One way is to integrate renewables over a wider geographic area to balance the grid or to use conventional power sources for compensation.⁷ Coal burning plants can be used but they are being phased out due to environmental concerns. Hydro accumulation or energy generation plants can be an option if they exist. Modern batteries are too expensive to be installed to compensate for the entire output of renewables. This leaves gas-burning plants as the only viable option since they can operate on stand-by and as back-up. Belgium is currently planning to phase-out its nuclear power plants by 2025 that currently produce about 60% of its power and to rely more on natural gas.⁸ Nuclear power plants however are usually operated at steady state and cannot quickly ramp up energy generation to offset supply fluctuations due to engineering requirements and maintenance.

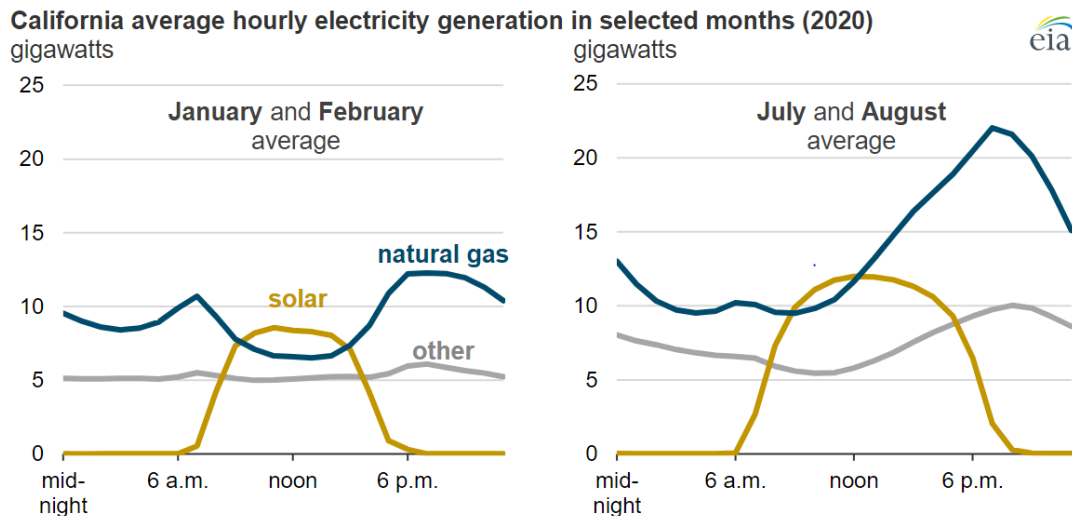


Figure 3. Natural gas is a commonly used option to cover fluctuations in renewable outputs.⁹

⁷ Managing Large-Scale Penetration of Intermittent Renewables. MIT Energy Initiative. 20 April 2011. <https://energy.mit.edu/wp-content/uploads/2012/03/MITEI-RP-2011-001.pdf>

⁸ No more nuclear plants for Belgium. 2 March 2002 <https://www.dw.com/en/no-more-nuclear-plants-for-belgium/a-465406>

⁹ In California, natural gas helps balance changes in electricity demand and solar output. 11 December 2020. <https://www.eia.gov/todayinenergy/detail.php?id=46236>

The EU may experience a gas deficit because of impending gas production closure in the Netherlands and declining gas production in the North Sea, and must find a way to replace that lost capacity.

The Netherlands' government decided to shut production at the Groningen gas field due to increased earthquake frequency attributed to gas extraction.^{10 11} In 2018 the government told 200 companies that they have four years to stop sourcing gas from Groningen field.¹² North Sea oil and gas output from its two main producers, Norway and the UK, are unlikely to meet the demand and extracting from the remaining deposits will be more expensive due to their smaller size and increased technical challenges.¹³

^{14 15}

Piped gas is cheaper than LNG and its delivery is more predictable.

Russia is currently a main supplier of piped gas and some LNG to Europe, competing with the US, Qatar and other LNG suppliers. Piped gas is cheaper in Europe than US-origin LNG.¹⁶ Russian-origin LNG is cheaper than the US as seen in purchases made by Lithuania.¹⁷ All LNG produced by Russian Novatek Company has been sold in advance for the next 20 years; no details about customers were reported.¹⁸

As a fungible commodity divorced from a static pipeline system, LNG supplies are more reactive to changes in price and demand. LNG went to Pacific Asia markets instead of Europe when demand increased in both areas due to cold weather and, in general, the Asian Pacific market has higher prices for LNG and suppliers prefer to sell there.¹⁹

¹⁰ Netherlands to shut Europe's biggest gas field to limit quake risk. 29 March 2018

<https://www.dw.com/en/netherlands-to-shut-europes-biggest-gas-field-to-limit-quake-risk/a-43190065>

¹¹ Earthquake in the Netherlands due to gas extraction. 12 May 2021 <https://www.brusselstimes.com/news/eu-affairs/57061/earthquake-in-the-netherlands-due-to-gas-extraction-fracking-knmi-mark-rutte-nederland/>

¹² Government tells 200 companies they have four years to stop sourcing gas from Groningen field after increasingly significant earthquakes, 23 January 2018
<https://www.theguardian.com/environment/2018/jan/23/gas-field-earthquakes-put-netherlands-biggest-firms-on-extraction-notice>

¹³ Assessing the future of North Sea oil and gas. Crystol Energy, 21 April 2016,
<https://www.crystolenergy.com/assessing-future-north-sea-oil-gas/>

¹⁴ Norway's giant Troll gas field third stage of production. 30 August 2021
<https://www.reuters.com/business/energy/norways-giant-troll-gas-field-begins-next-stage-production-2021-08-30/>

¹⁵ Drilling in the Barents Sea Could Lead to Demanding Cooperation Between Norway and Russia. 23 June 2021
<https://www.highnorthnews.com/en/drilling-barents-sea-could-lead-demanding-cooperation-between-norway-and-russia>

¹⁶ Klaipeda-based LNG terminal is an energy failure for Lithuania. 27 March 2021 <https://rueconomics.ru/507733-klaipedskii-spg-terminal-obernulsya-energeticheskim-provalom-litvy>

¹⁷ The new load from Novatek arrived at the Klaipeda regasification point. 1 April 2021,
<https://www.delfi.lt/ru/news/economy/na-klajpedskij-tspg-prishel-novyj-gruz-gaza-ot-novateka.d?id=86845015>

¹⁸ All of liquefied natural gas from Russia's Arctic for next 20 years sold in advance – Novatek, 28 April 2021,
<https://www.rt.com/business/522332-russia-arctic-lng-supply-agreements/>

¹⁹ Europe frantically purchases Russian gas even in spring. 4 April 2021
<https://vz.ru/economy/2021/4/4/1092867.html>

Europe Needs Russian Gas

In 2020 Russia supplied more gas to Europe than the US. Moreover, in January 2021 due to harsh weather, European countries increased gas purchases by 40 % on average with some countries substantially above this average, such as Italy (increased by 221.5%), France (77.3%), Germany (32.4%), and the Netherlands, itself a gas producing and exporting country (21.2%). Poland has a 20-year LNG contract with the US but still increased its purchases of Russian piped gas by 89.8%.²⁰ European experts estimate that Europe will need 20% more gas in the future.

Country	Export volume in millions of tons
Qatar	77.8
Australia	75.4
USA	33.8
Russia	29.3
Malaysia	26.2
Nigeria	20.8
Indonesia	15.5
Trinidad and Tobago	12.5
Algeria	12.2
Oman	10.3

Table 1: 2019 main exporters of LNG worldwide

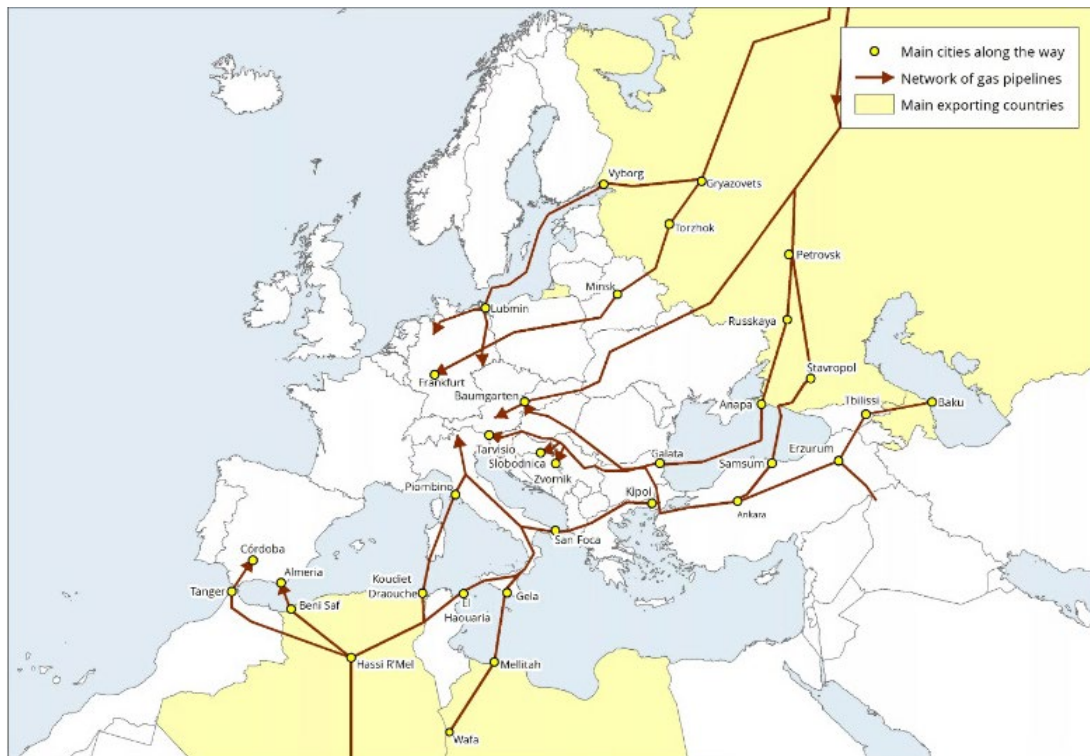


Figure 4: Gas pipeline supply network to Europe²¹

²⁰ Energy discussion at the Novosibirsk, Russia-based Aftershock news program, 9 February 2021

<https://www.youtube.com/watch?v=PbmjeLDgkHg>

²¹ Gas pipelines that supply Europe. Source: Gazprom and EU.

<http://gassupplypanmubi.blogspot.com/2017/03/gas-supply-europe.html>

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In principle, Europe can source its natural gas supplies from Qatar, the US, Russia, and Oman (Iran could be another option but currently it is not politically available). Algiers cannot increase its exports due to internal needs. Russia plans to increase LNG production by a factor of three or maybe four based on its first LNG project performance. The Yamal-SPG was able to double its production from 14B in 2018 to 28.5B cubic meters of gas in 2020 with a new section coming online soon.²² In 2020 when Azerbaijan increased its exports to 13.8, the increase went to Southern Europe, such as Italy, Greece and Bulgaria,²³ but the gas has not been made available to the other European countries.

The EU has built a distribution system for Nord Stream 1 and 2 gas. European energy corporations that privately funded its construction most likely will pressure governments for policies that would allow these costs to be recouped.

Major pipelines for the Nord Stream 1 and 2 gas have already been built in Europe. The main European contributors for the Nord Stream-2 maritime section are Wintershall, Uniper, OMV, and Royal Dutch Shell Companies. The project, in addition to the maritime segment, includes ground segments, inter-connectors, local distribution centers, and gas compression stations. The EUGAL pipeline in Germany cost 2.276B euro and the extension to Czechia 540M euro. Overall, there are more than 670 companies involved with Nord Stream II project, and many of them made significant investments in the project.²⁴ French Engie invested 700M euro in the project, although France will not rely much on its gas.²⁵ Due to the US sanctions many of the companies stopped investing in the project²⁶ and if the project never becomes operational these costs will be lost. See Appendix D for the history of Soviet/Russian gas supplies to Europe.

²² Yuri Podolyaka. Russia won the gas war, 12 March 2021, <https://www.youtube.com/watch?v=FNBnxr5OKZw>

²³ Azerbaijan raised gas exports by 17% to 13.8 bcm in 2020. <https://www.enerdata.net/publications/daily-energy-news/azerbaijan-raised-gas-exports-17-138-bcm-2020.html>

²⁴ Energy discussion at the Novosibirsk, Russia-based Aftershock news program, 9 February 2021 <https://www.youtube.com/watch?v=PbmjeLDgkHg>

²⁵ Will France work to save Nord Stream from the US sanctions? 12 March 2020 <https://www.dw.com/ru/бюджет-ли-франция-спасать-северный-поток-2-от-санкций-сша/a-52728378>

²⁶ There have been a number publications about Nord Stream at Germany's DW websites, such as Wintershall stopped crediting the project, 24 February 2021 <https://www.dw.com/ru/wintershall-dea-bolshe-ne-kredituet-severnyj-potok-2-chto-jeto-oznachaet/a-56677171>; Munich Re Syndicate Ltd. Left the Nord Stream-II project, 23 February 2021, <https://www.dw.com/ru/strahovaja-kompanija-munich-re-syndicate-ltd-vyshla-iz-proekta-severnyj-potok-2/a-56664782>; Bilfinger SE stopped working on Nord Stream II, 19 January 2021, <https://www.dw.com/ru/firma-bilfinger-se-iz-frg-prekrashhaet-rabotu-s-nord-stream-2/a-56278324> and similar publications.

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Figure 5: Major pipelines to take Nord Stream gas to European customers

Estonia, Latvia, and Lithuania planned disconnection from BRELL most likely will result in more pressure on European power generation.

Estonia, Latvia and Lithuania declared several years ago their intent to disconnect from BRELL (Belarus-Russia-Estonia-Lithuania-Latvia power grid) and to synchronize their power grid with Europe. The Baltic states need to purchase energy from outside—Estonia has shut down its power plants due to pollution, Lithuania shut down its NPP when it joined the EU, and Latvia currently produces only as much as needed but must purchase power in cases of short-term increased demand. They can purchase electricity from Russia as they currently do²⁷ or continue purchasing gas and increase their domestic production. Currently, a significant share of their LNG comes from Russia, with growing demand the increase would most easily be covered by Russia.²⁸

There are recent examples of increased natural gas consumption due to energy deficit.

MIT analysis of various conventional power sources, including coal, natural gas and nuclear power plants, to stabilize a grid having a significant share of renewable power generation concluded that “natural gas-fired power plants provide the greatest generation flexibility to mitigate large-scale penetration of intermittent renewables.”²⁹

²⁷ Russia doubles electricity exports as cold winter and hot summer ensure lucrative price environment. 4 July 2021. RT. <https://www.rt.com/business/527965-electricity-exports-russia-surge-record/>

²⁸ Energy expert Boris Martsinkevich. Geoenergetika.

²⁹ Managing Large-Scale Penetration of Intermittent Renewables. MIT Energy Initiative. 20 April 2011. <https://energy.mit.edu/wp-content/uploads/2012/03/MITEI-RP-2011-001.pdf>

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In early 2021, Gazprom significantly increased its sales of piped gas to the EU. Some factors included the variability of green energy production and increase of LNG prices in Asia resulting in diversion of LNG traffic from Europe. Piped gas was used to offset these losses in capacity and to balance power grids.³⁰

Moreover, during cold weather in winter 2021 Europe experienced loss of power production from renewables while customer demand for power went up. European utilities had to increase purchases of coal from Russia to cover their energy deficit,³¹ because there was no gas available.³² With a higher share of renewables in the future and fewer or no coal-burning plants, Europe may experience higher energy deficits and therefore an increased need for back-up power. California has recently experienced rolling black-outs and customer cuts after steadily increasing its share of renewables but not sufficiently increasing non-renewable power generation capacity to compensate for intermittent power supply from renewables.³³

In conclusion, Europe must find a way to supplement its energy production as it moves to include more wind and solar production into its power generation scheme. The EU could accommodate its growing share of renewables on the grid with gas-burning plants. Political considerations may prevent purchasing this gas from Russia. Without making allowances for the changes in the overall energy capacity, the EU could face more costly and more difficult to manage solutions and make the cost of power for European consumers and European manufacturers higher.

The work was funded by the Los Alamos National Laboratory's Office of National Security and International Studies.

³⁰“Газпром” в январе установил рекорд по экспорту газа [Gazprom reached a record of gas exports in January]. TASS, a leading Information Agency of Russia, 2 February 2021. <https://tass.ru>

³¹ Evropa rezko uvelichila zakupku uglja v Rossii. [Europe drastically increased purchases of coal in Russia]. 14 January 2021. <https://www.bfm.ru/news/462712>

³² Analitik Yushkov ob'yasn timer, pochemu Evropa ne cmozhet otkazat'sya ot possiyskogo uglja. [Russia-based energy expert Igor Yushkov explained why Europe cannot stop buying Russian coal] Yushkov said that purchases of coal was result of lack of available gas to buy. 20 June 2021. https://rueconomics.ru/525716-analitik-yushkov-obyasnil-pochemu-evropa-ne-smozhet-otkazatsya-ot-rossiiskogo-uglja?utm_source=yxnews&utm_medium=desktop&utm_referrer=https%3A%2F%2Fyandex.ru%2Fnews%2Fsearch%3Ftext%3D

³³ Why renewables aren't to blame for California's blackouts. 25 August 2020 <https://www.nationalgeographic.com/science/article/why-renewables-arent-reason-california-blackouts>

Appendix A. Solar Power Production Variability

Solar energy production is inherently variable and in both predictable and unpredictable ways. The predictable variations include daily (no sun at night), and seasonal (fewer daytime hours in the winter than in summer) changes, as well as daily and seasonal angles at which sunlight hits the panel that corresponds to different efficiency generation rates and efficiency changes due to temperature fluctuations (high solar cell temperatures degrade performance). Predictable changes can be forecasted using special software.³⁴ The unpredictable changes include variations caused by cloud coverage, increased level of dirt, dust or pollution, and accumulation of snow on panels.

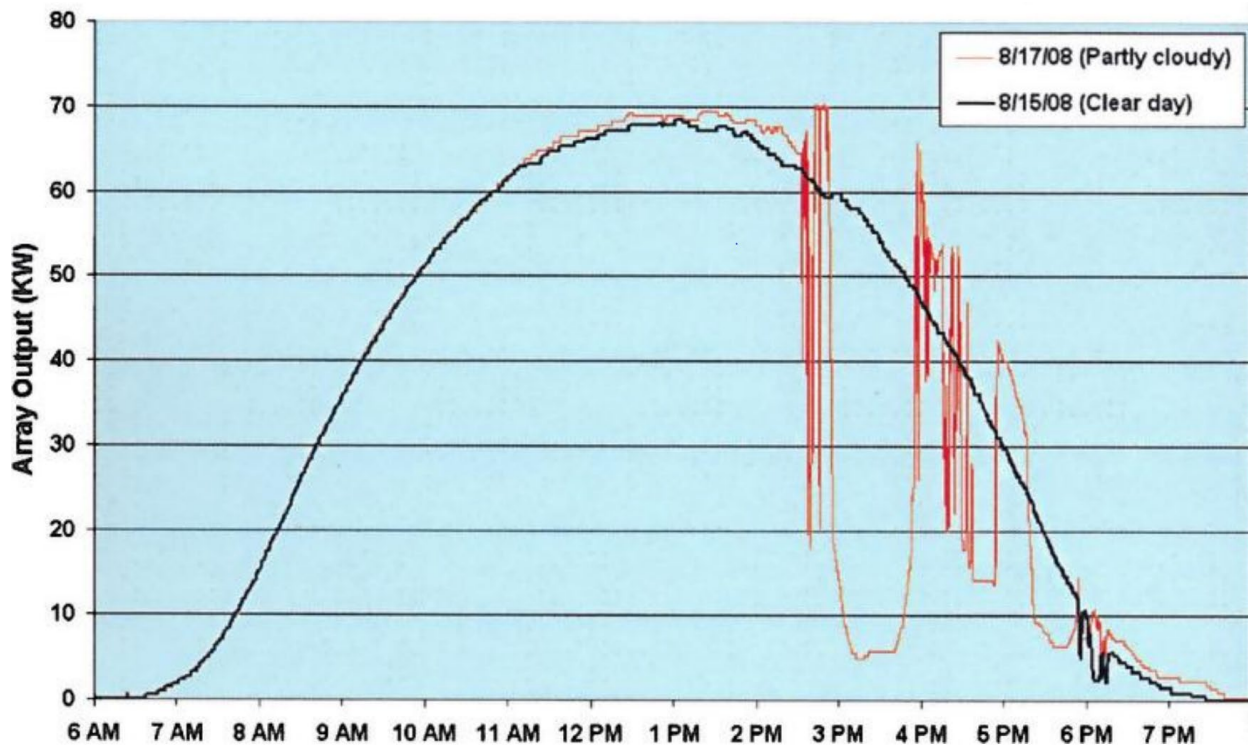


Figure 6: Variability of photovoltaic energy output is shown for two days in August 2008 at the Nevada 70 kW polycrystalline array (data taken every 10 seconds)³⁵

³⁴ For example Trace Software International specializes on development of software solutions for electrical installations, including solar. <https://www.trace-software.com>

³⁵ PG&E Presentation 16 November 2010 to the California Energy Commission, http://www.energy.ca.gov/2011_energy_policy/documents/2010-11-16_workshop/presentations/09_Schinker_PGE_Applying_Large_Scale_Energy_Storage.pdf

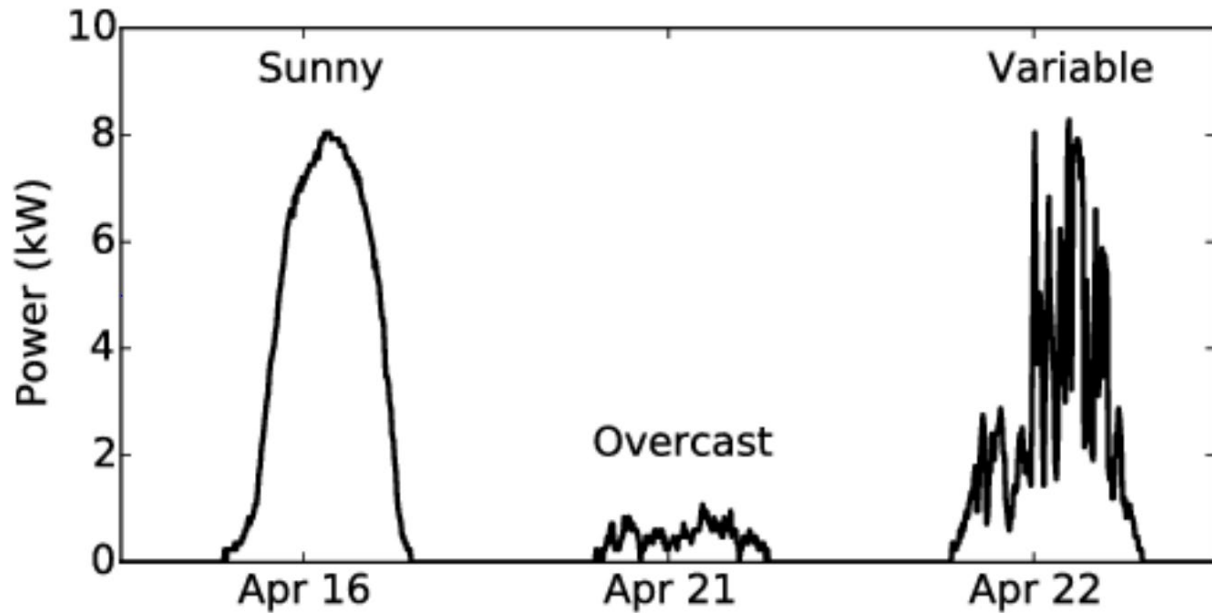


Figure 7: Variability of solar power production depending on times of the day and weather conditions in April 2015³⁶

Solar power production can fluctuate very fast, making it difficult to forecast even with modern satellites that provide images over 10 to 30 minute timeframes:³⁷

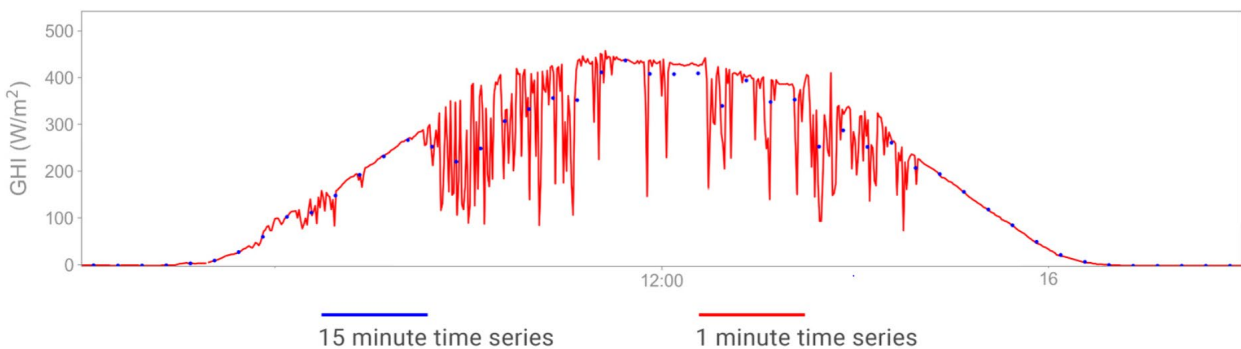


Figure 8: Observed fluctuations in solar production over 24 hour period

³⁶ Distributed Rate Control for Smart Solar Arrays. Stephen Lee, Srinivasan Iyengar, David Irwin and Prashant Shenoy. e-Energy'17: Proceedings of the Eighth International Conference on Future Energy Systems. May 2017 pp.34-44. 16 May 2017. <https://dl.acm.org/doi/10.1145/3077839.3077840>

³⁷ Data from Solargis software company specializing in forecasting software for solar power projects. <https://solargis.com/products/evaluate/overview>

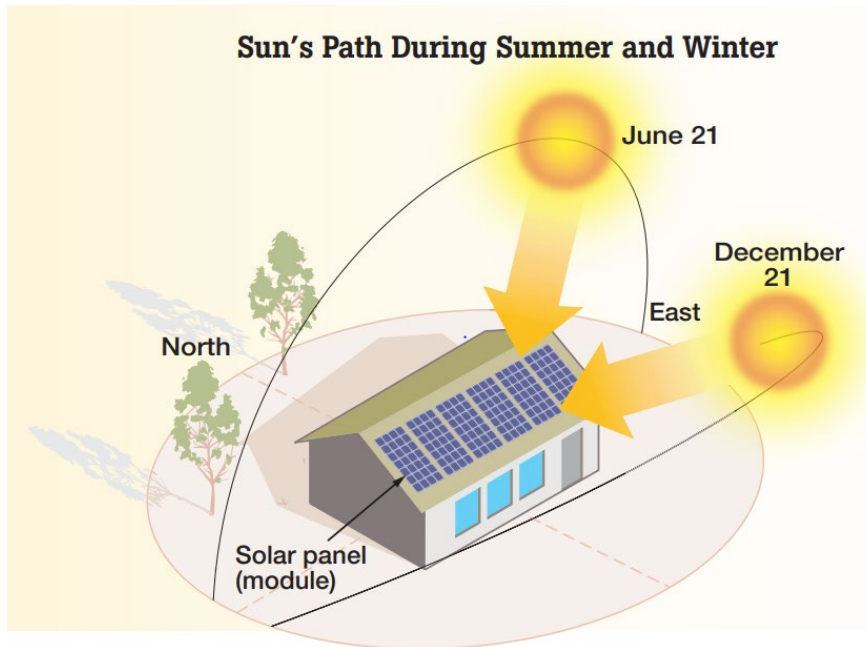


Figure 9: Department of Energy illustration of the seasonal solar production depicting positions of the sun in summer and winter³⁸

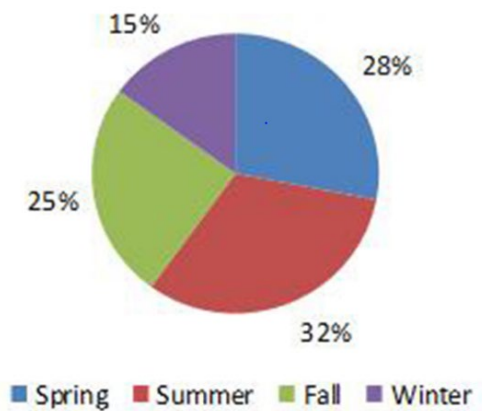


Figure 10: Seasonal solar production for New England³⁹

The power grid operators have to compensate for fluctuations of power generated in photovoltaic systems and the rapid fluctuations can lead to power quality problems, for example, changes in grid voltage and frequency variations.

The National Renewable Energy Laboratory (NREL) in collaboration with Southern California Edison (SCWE), Quanta Technology, Satcon Technology Corporation, Electrical Distribution Design (EDD) and

³⁸ A Consumer's Guide to Solar Electricity for the Home. January 2009.

<https://www1.eere.energy.gov/solar/pdfs/43844.pdf>

³⁹ The Energy Miser blog by Mark Durrenberger. New England Clean Energy

<https://newenglandcleanenergy.com/energymiser/2017/10/10/why-october-is-a-trick-not-treat-for-solar/>

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Clean Power Research (CPR) issued a handbook to assist incorporation of photovoltaic systems into the power grid.⁴⁰ The handbook provides ways to assess impact from high share of solar and presents various mitigation techniques. Unfortunately, the book does not contain actual data from utilities' operation demonstrating costs and efforts taken to accommodate significant share of solar energy in power mix. Another NREL report, published in 2015, listed utilities with the highest fraction of energy sold back, which corresponds to solar power generated by customer-installed solar panels, as 2% and 1.7% in Hawaii (Hawaii Electric Light Co., Inc. and Kauai Island Utility Cooperative) and 1.1% in Massachusetts (NSTAR Electric Company); the numbers are too small to be considered a significant share of solar power.⁴¹ Research has been ongoing worldwide on potential solutions.^{42,43,44,45}

⁴⁰ High-Penetration PV Integration Handbook for Distribution Engineers. Technical Report. NREL/TP-5-D00-63114. January 2016. <https://www.nrel.gov/docs/fy16osti/63114.pdf>

⁴¹ Compensation for Distributed Solar: A Survey of Options to Preserve Stockholder Value. Technical Report. NREL/TP-6A20-62371. September 2015. <https://www.nrel.gov/docs/fy15osti/62371.pdf>

⁴² Impact of rapid PV fluctuations on power quality in the low-voltage grid and mitigation strategies using electric vehicles. N.B.G. Brinkel et al., International Journal of Electrical Power & Energy Systems, vol. 118, June 2020, 105741. <https://www.sciencedirect.com/science/article/pii/S0142061519319994>

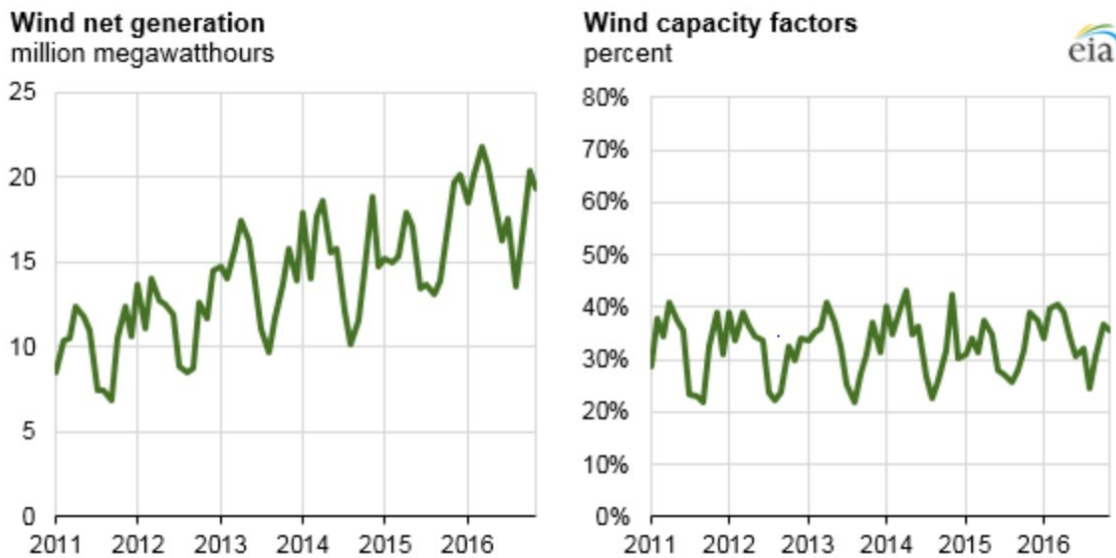
⁴³ Study on Power Fluctuations Dispatch and Capacity Design of Short Period Power Fluctuations Compensation System in Consideration of Power Loss. Akihiro Teguri et al., Electrical Engineering in Japan. 17 November 2015. <https://onlinelibrary.wiley.com/doi/abs/10.1002/eej.22705>

⁴⁴ Compensation of power Fluctuations in PV System through Energy Storage System. Kritika Vivek Narkhede. International Journal of Innovative Technology and Exploring Engineering (IJITEE). ISSN: 227-3075, vol. 8, is. 12, October 2019 <https://1library.net/document/1y9o3lry-compensation-power-fluctuations-pv-energy-storage.html>

⁴⁵ Impacts of Solar Intermittency on Future Photovoltaic Reliability. Yun Yin, Annalisa Molini & Amelicare Porporato. Nature Communications 11, Article Number: 4781 (2020) 22 September 2020 <https://www.nature.com/articles/s41467-020-18602-6>

Appendix B. Wind power production

Wind power is another renewable source of energy that has seen steady worldwide growth. Wind power is mostly produced by a horizontal-axis wind turbine ranging in size from 2.5 m in diameter and 1 kW for residential applications to 100+ m in diameter and 10+ MW for offshore applications and having on average about 50% of maximum efficiency. However, the turbines do not produce electricity continuously, they have a variable output, and on average the capacity factor (an average power output divided by its maximum power capability) is between 0.26 to 0.52 with offshore turbines' capacity factors higher on average than land-based due to offshore stronger winds. Over time there have been significant improvements in efficiency and capacity factor values.⁴⁶



Source: U.S. Energy Information Administration, [Electric Power Monthly](#)

Figure 11: Wind-power production data for the U.S.⁴⁷

However, wind power has presented challenges related to its inherent short-term and long-term variability.⁴⁸ Short-term variability include variations within the minute that do not have much impact on a grid, variations within the hour, from hour to hour, and long-term variability that includes monthly and seasonal variation and inter-annual variations.

⁴⁶ Wind energy factsheets. Center for Sustainable Systems of the University of Michigan. September 2020. <http://css.umich.edu/factsheets/wind-energy-factsheet>

⁴⁷ EIA <https://www.eia.gov/todayinenergy/detail.php?id=31032>

⁴⁸ Understanding Variable Output Characteristics of Wind Power: Variability and Predictability. <https://www.wind-energy-the-facts.org/understanding-variable-output-characteristics-of-wind-power-variability-and-predictability.html>

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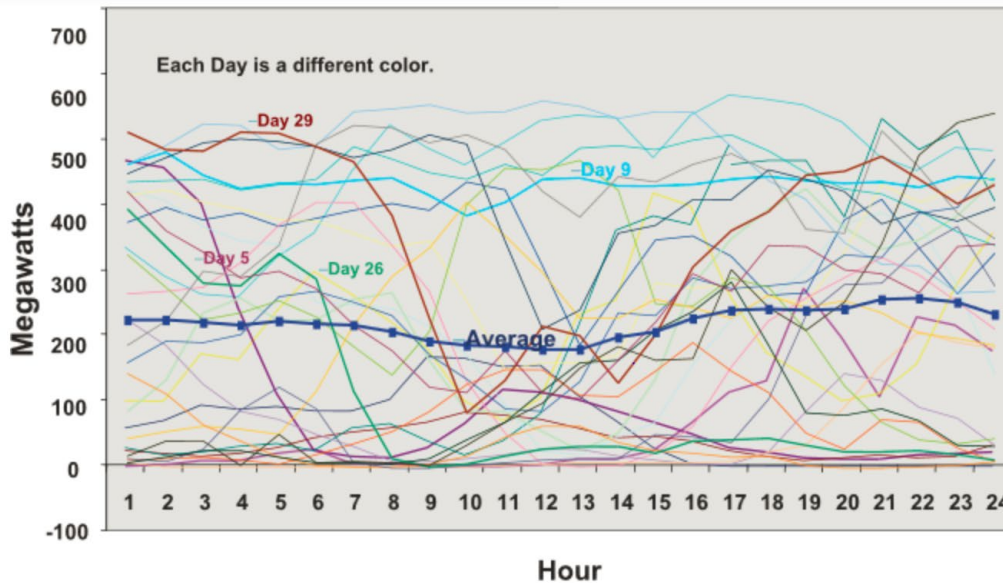


Figure 12: Hourly wind power output on 29 different days in April 2005 at Tehachapi WRA, California⁴⁹

In 2006 Physics Today noted that, based on the Wind Report 2005 by the E.ON Netz electrical utility of Germany, wind power can replace traditional power stations only to a limited extent due to power output fluctuations and that introduce risks to the power grid. The utility's report concluded that conventional generating capacity of about 90% of the wind capacity has to be added to the grid as backup.^{50,51}

⁴⁹ PG&E Presentation 16 November 2010 to the California Energy Commission, http://www.energy.ca.gov/2011_energypolicy/documents/2010-11-16_workshop/presentations/09_Schinker_PGE_Applying_Large_Scale_Energy_Storage.pdf

⁵⁰ E.On. Netz. Wind Report 2005 <http://docs.wind-watch.org/EonWindReport2005.pdf>

⁵¹ Tough questions about wind energy. Frits de Wette, University of Texas at Austin. 1 August 2006. Physics Today 59, 8,12 (2006) <https://doi.org/10.1063/1.4797413>

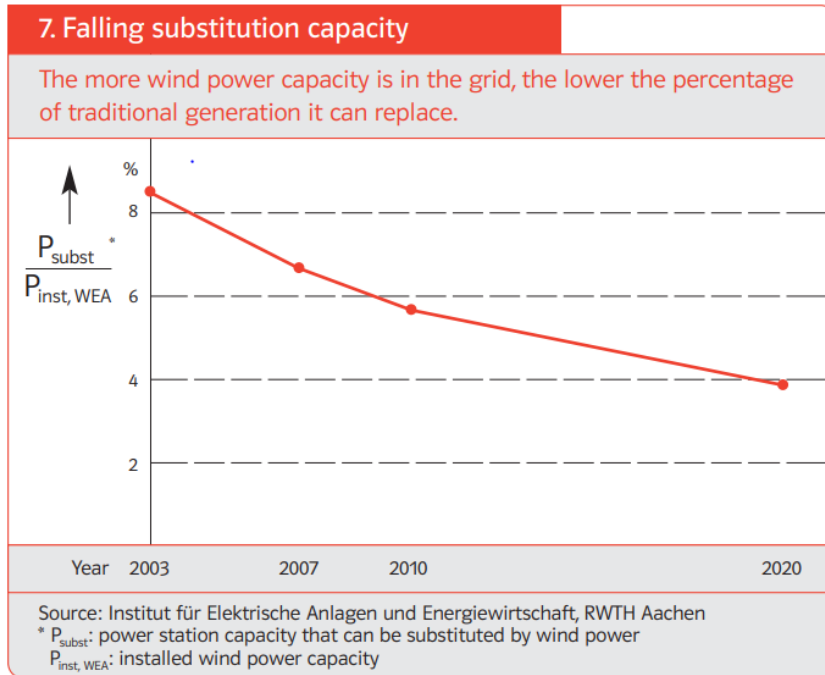


Figure 13: Relation between Wind capacity and ability to absorb variation in a power grid

Moreover, the backup capacity must be on a standby or available for rapid ramping up because it is difficult to forecast wind output.

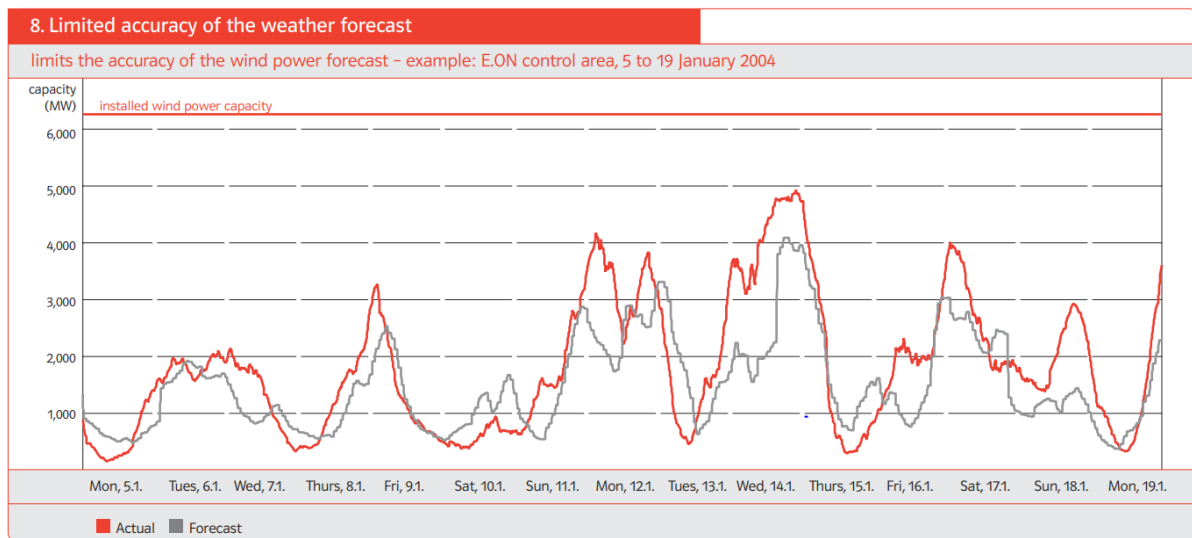


Figure 14: Difference between forecast and recorded wind power generation

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Grid interconnectivity over larger areas where wind turbines operate makes it possible to balance the grid but requires investments in grid upgrades.⁵²

German manufacturers of wind turbine noted a slump in expansion that began in 2018 and got worse in 2019 resulting in job cuts and led some companies to insolvency, indicating lower interest in wind power from utilities.⁵³ Moreover, recently Svenska kraftnaet power grid company of Sweden expressed concerns that growing wind power production in Europe could make it harder for Sweden to acquire power to cover peak demands in 2020/2021 winter. The Swedish transmission system operator estimated that Sweden may need to import 1,600 MW of electricity to cover peak consumption during winter, based on previous winter usage.⁵⁴

⁵² Understanding Variable Output Characteristics of Wind Power: Variability and Predictability. <https://www.wind-energy-the-facts.org/understanding-variable-output-characteristics-of-wind-power-variability-and-predictability.html>

⁵³ German onshore wind power – output, business and perspectives. Clean Energy Wire. 30 July 2020. <https://www.cleanenergywire.org/factsheets/german-onshore-wind-power-output-business-and-perspectives>

⁵⁴ Wind reliance could hamper Sweden's winter power supplies. May 31 2021 <https://www.nasdaq.com/articles/wind-reliance-could-hamper-swedens-winter-power-supplies-2021-05-31>

Appendix C. Balancing supply and demand across a power generation scheme

The intermittent and variable power generation exaggerate issues related to balancing the grid to meet variable consumers' demands. As demand draws off more power, supply must be increased, and as demands slow, supply must be decreased. However solar and wind output depends on nature, not on a dispatcher's request. The grid needs options to balance the grid such as increasing generation, importing power from other sources or restrictions on consumption.

Conversely, renewable power sources can also overproduce forcing either decreased output or direct the power to storage. As a consequence, the grid management has to be flexible to accommodate for these changes, along with introducing cycling, batteries or other storage systems, such as compressed air storage.

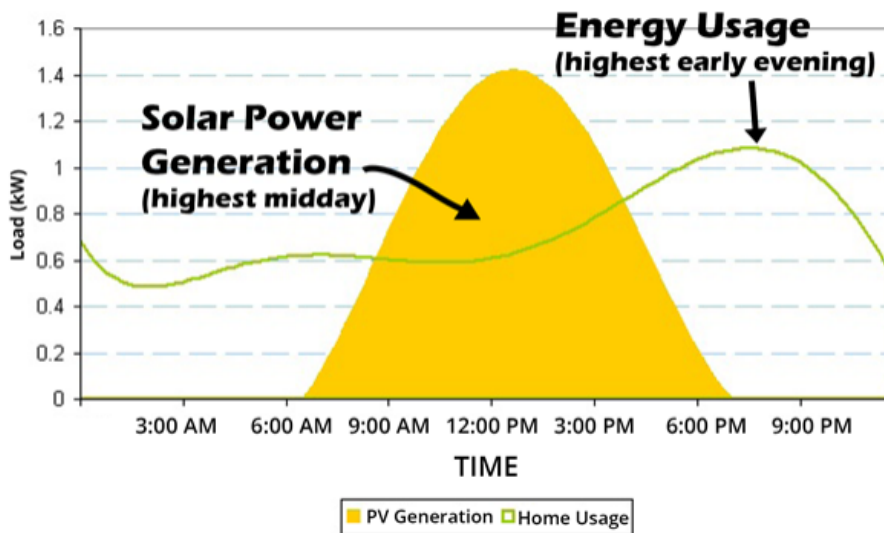


Figure 15: Illustration of relationship between solar (photovoltaic, or PV) power production and average household energy usage⁵⁵

Introduction of a significant share of solar and wind power production can make grid operation more complicated and require built-in provisions for drastic adjustments to balance generation and power consumption. Operating conventional power sources outside of the steady-state regime to balance these variations can result in lower efficiency, higher costs and more emissions as a consequence.

⁵⁵ New SCE Time of Use Rate Periods Will Cut Benefit of Solar by Up to 50% (TOU explained). Explanation for the net metering changes introduced by the Southern California Edison Company for its customers. 21 October 2018. Sunpower by Green Convergence. <https://www.greenconvergence.com/blog/2018/october/new-sce-time-of-use-rate-periods-will-cut-benefi/>

Grid flexibility has been explored in a number of studies, for example, the cost-benefit analysis of curtailing renewable excess power production or storing it,⁵⁶ considerations for required back-up generation,⁵⁷ estimation of required energy storage for renewable energy to support residential consumption,⁵⁸ and the methodology to use wind power patterns in different European countries for the European electricity transmission system.⁵⁹

Different energy storage considerations include batteries (for ex., Moss Landing Energy Storage Facility in California, USA), compressed air storage (for ex., McIntosh CAES Plant in Alabama, USA), molten salt storage (for ex., Ouarzazate Solar Power Station in Morocco), flywheel (for ex., Beacon New York Flywheel Energy Storage Plant in New York, USA) and pumped hydro storage (for ex., Bath County Pumped Storage Station in Virginia, USA) with new technologies under consideration, such as hydrogen production. All these solutions require funding and engineering costs to accomplish and coordinate their operation within the grid in addition to the costs of building and operating renewable energy systems, and make grid management a more complex endeavor.

⁵⁶ The energetic implications of curtailing *versus* storing solar- and wind-generated electricity. Charles J. Barnhart, Michael Dale, Adam R. Brandt and Sally M. Benson. *Energy Environ. Sci.*, 2013, 6, 2804-2810.
<https://pubs.rsc.org/-/content/articlehtml/2013/ee/c3ee41973h>

⁵⁷ Grid vs. storage in a 100% renewable Europe. Florian Steinke, Philipp Wolfrum, Clemens Hoffmann. *Renewable Energy*, vol. 50, February 2013, pp. 826-832.

<https://www.sciencedirect.com/science/article/abs/pii/S0960148112004818>

⁵⁸ Estimation of Energy Storage and Its Feasibility Analysis. Mohammad Taufiqul Arif, Amanullar M.T.Oo and A.B.M. Shawkat Ali. In: *Energy Storage – Technologies and Applications*. DOI: 10.5772/52218
<https://www.intechopen.com/books/energy-storage-technologies-and-applications/estimation-of-energy-storage-and-its-feasibility-analysis>

⁵⁹ How synchronous is wind energy production among European countries? F. Monforti, M. Gaetani and E. Viganti. *Renewable and Sustainable Energy Reviews*, vol. 59, June 2016, pp. 1622-1638.
<https://www.sciencedirect.com/science/article/pii/S1364032115017013>

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Appendix D. History of Soviet/Russian gas supplies to Europe.

Europe became interested in sourcing gas from Russia several decades ago.^{60 61 62} In the 1960s discussions took place between Western European politicians and USSR leadership on supplying gas to Europe. In 1967 USSR started supplying gas to its European satellites via “Bratstvo” [Brotherhood]. In 1970 West Germany and the USSR signed the “Agreement of the Century,” trading large diameter German-made pipes for Soviet gas. Under this agreement USSR built an extensive pipeline system in Ukraine and made Ukraine a crucial player for transiting gas to Europe.

Subsequent to the oil crisis of 1973, Europe began relying more on gas to cover its energy needs and began exploring additional options to acquire gas from the Soviets. In the early 1980s, Sweden and Finland expressed an interest to purchase the gas directly from the Soviet Union- not via Germany- and commenced feasibility studies for the Northern-European Pipeline. In 1996 Sweden and Finland withdrew from the project and Denmark took over in the pipeline project development. For the next ten years progress was minimal due to Russian stalling.

After the Soviet Union collapsed Russia was interested in using Ukraine’s gas transit system to pump gas to Europe. Russian and Ukrainian officials discussed establishing a joint consortium, which would encompass Ukraine’s gas pipeline system. Ukraine saw this as a chance for Ukraine to maintain its monopoly position on Russian gas transit to Europe. In 2002 Russia and Ukraine signed an agreement to establish this consortium on 50:50 basis, and Germany expressed its interest to join the project. The joint enterprise was going to develop a business plan of its operations, including modernization of Ukraine’s transit system.

However, changes in Ukraine political leadership did not favor the joint project and it was not implemented. In early 2006 a smaller proposal to transfer the pipeline under construction in Ukraine (Bogochary-Uzhgorod and Alexandrov Gay-Novoposkovsk-Uzhgorod) was proposed under the joint consortium management. This project also collapsed in 2009.

In the meantime, the first pipeline bypassing Ukraine was completed in 1999 moving gas from Russia to Europe via Belarus and Poland. It was followed by completion of the Blue Stream from Russia to Turkey in 2003, the NordStream-I to Germany in 2011, and the Turk Stream to Turkey, which was initially envisioned to Bulgaria, in 2020. In 1999 Ukraine transited 141 billion cubic meters of gas to Europe, and by 2007 that had fallen to 137 billion cubic meters. Currently, Ukraine has a five-year gas transit contract with Russia’s Gazprom through 2024 for 40 billion cubic meters, plus any additional transit purchasing

⁶⁰ Pivnechiy potik -2: Shcho vtratat Ukrainy? [Northern Stream- 2. What will Ukraine lose?] TV show by Alexander Kolodniy at the “Nash” channel with an overview of the history of the NordStream-2, its implementation and consequences for Ukraine, whether it results for price increase for Ukrainian gas consumers and whether Ukraine still has a chance to build a largest gas hub on 12 June 2021 www.youtube.com/watch?v=16OlqaWafJQ

⁶¹ Ukraine-based energy expert Dmitry Marunich gave an interview to the First Cossack TV channel on July 11 2021. www.youtube.com/watch?v=BptahguDqTk

⁶² Ukraine-based economist Viktor Skarshevsky at the Nash TV program on July 21 2021 <https://www.youtube.com/watch?v=BltrvLeL0S8>

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volume. This transit will likely continue in the future due to immense Ukrainian underground storage facilities despite the spite of wear and tear of the Ukraine's pipeline transit system.

In addition to the main transit lines for gas from Russia, a number of interconnecting pipelines were built across Europe, making distribution of gas easier and providing redundancy. The last ones were done in July 2021 when Serbia and Hungary completed an interconnector with the Turk Stream allowing the Central European countries to obtain Russian gas bypassing Ukraine.

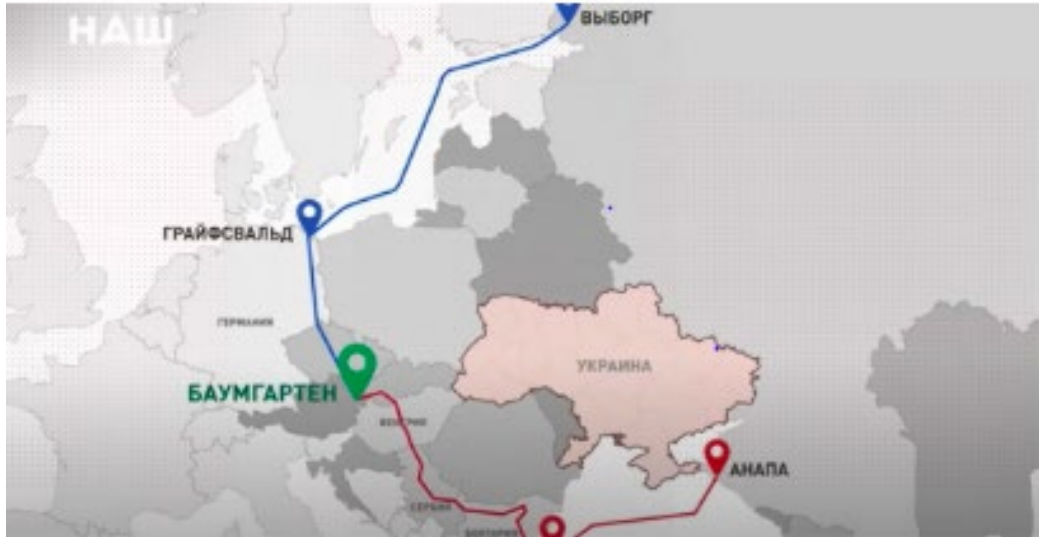


Figure 16: The NordStream and Turk Stream pipelines meet in Baumgarten, Austria, making it a hub for Russian gas in Europe